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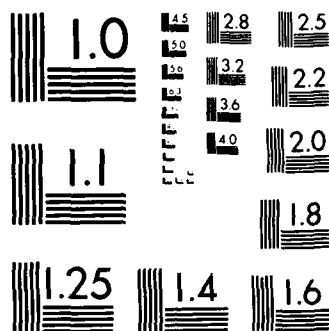
SOLAR FLARES AND MAGNETOSPHERIC PARTICLES:
INVESTIGATIONS BASED UPON THE (U) LOUISIANA STATE UNIV
BATON ROUGE DEPT OF PHYSICS AND ASTRONOM J P WEFEL
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ANNUAL LETTER REPORT

ONR Contract N00014-83-K-0365

"Solar Flares and Magnetospheric Particles:
Investigations Based Upon the ONR-602 and ONR-604 Experiments"

John P. Wefel
Principal Investigator

Covering the Period: 5/1/85 - 6/30/86

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SOLAR FLARES AND MAGNETOSPHERIC PARTICLES:
INVESTIGATIONS BASED UPON THE ONR-602 and ONR-604 EXPERIMENTS

ONR Contract N00014-83-K-0365

I. INTRODUCTION:

The report covers the third year of the contract, cited above, which involves fundamental investigations of the charged particle component in the Geospace environment. The project involves analysis of the data returned from the ONR-602 (Phoenix-1) experiment on the S81-1 in mission in 1982, correlation of the Phoenix-1 dataset with other measurements and scientific planning for the launch and operation of a sister experiment, ONR-604, on the CRRES mission. During the past year significant progress was made in understanding the ONR-602 instrument performance and the dataset, in analyzing the low-energy protons observed in the equatorial belt, in summarizing solar energetic particle observations, and in working with the CRRES/SPACERAD Science Team.

II. Personnel:

The personnel engaged in this analysis effort consist of the principal investigator; one graduate student, Mr. M. A. Miah, working full-time on the project; a Senior Research Associate, Dr. T. G. Guzik working part-time on the analysis; and a Research Associate, Dr. J. M. Mitchell who has joined our group and replaces the programmer/analyst in this effort. The addition of Dr. Mitchell increases the research staff available for the analysis. In addition, several undergraduate students are employed to help with programming and routine data handling tasks.

III. Facilities:

The majority of the data analysis has been handled, heretofore, with a small PDP-11/73 based data processing system in the High Energy Astrophysics/Space Science group at LSU, augmented by the use of the university's SNCC IBM 3084 mainframe computer system. In the past year we have devoted considerable effort to bring the analysis software to our newly acquired VAX-11/750 based Experimental Physics Data System (EPDS) which improves compatibility with the data analysis system at the University of Chicago, removes the program size limitation inherent in the PDP-11 system and simplifies the data analysis and processing tasks.

During the past year, we acquired a vector pen plotter (Calcomp 1044) which has now been interfaced to the EPDS and is beginning to come "on-line" for plotting the many detector counting rates in the ONR-602 data. Work on interfacing our plotting library to his device is on-going as are preparations for using it for the CRRES (ONR-604) analysis.

IV. Reports and Presentations:

No papers were published in journals during this period but several reports were given at National/International meetings and one paper appeared in final form.



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- (1) "The Experiment for High Energy, Heavy Nuclei Composition (ONR-604)," J. A. Simpson, M. G. Munoz, M. Perkins and J. P. Wefel, in CRRES/SPACERAD Experiment Descriptions, eds. M. S. Gussenhoven, E. G. Mullen and R. C. Sagalyn, (Air Force Geophysics Laboratory, 1985, Hanscom AFB, MA), p. 163.
- (2) "Particle Precipitation at Low Altitudes near the Equator," M. A. Miah, T. G. Guzik and J. P. Wefel, EOS, 66, 1029 (1985).
- (3) "Equatorial Particle Precipitation," presented by M. A. Miah to the 5th Course of the International School of Cosmic Ray Astrophysics (A NATO Advanced Study Institute) held 1-9 June, 1986, at the Ettore Majoranna Centre, Erice, Sicily, Italy.

Several manuscripts are currently in preparation:

- (1) Dr. T. G. Guzik was invited to prepare a summary/review paper on Solar Energetic Particles and Gamma Rays for a special issue of Solar Physics. This work is in progress and should be completed this fall.
- (2) A paper for J.G.R. summarizing our observations of energetic (~ 1 MeV) protons near the geomagnetic equator at low altitudes during 1982 is in preparation and should be submitted in the next several months. This data forms the basis of the Ph.D. thesis of Mr. M. A. Miah, to be completed in the next year to 18 months.

V. Research Effort:

The work performed during the past year can be divided into three areas: (i) Solar flare synthesis (ii) Data Processing, programming and instrument response, and (iii) Magnetospheric particle investigations. Our analysis effort has focussed on resolving problems encountered in our initial studies, developing the software tools needed to read, reduce and analyze the PHRET tapes from Phoenix-1, and finalizing work on several of the projects begun in previous years -- particularly the low energy equatorial proton observations -- in preparation for publication of the results.

A. Solar Flare Synthesis

In this area the work has been under the direction of Dr. T. Gregory Guzik and focussed on summarizing not only our Phoenix-1 data but a wide range of recent results on solar flares and solar energetic particles that have appeared in the literature. This summary will include:

- a) Particle energy spectra
- b) Elemental composition and its relationship to the composition of the solar photosphere and solar coronal
- c) Time and energy variations
- d) Flare size effects
- e) Isotopic composition of solar energetic particles
- f) Particle charge state determinations
- g) Electron and proton observations
- h) Gamma ray line measurements and comparison to solar energetic particle measurements.

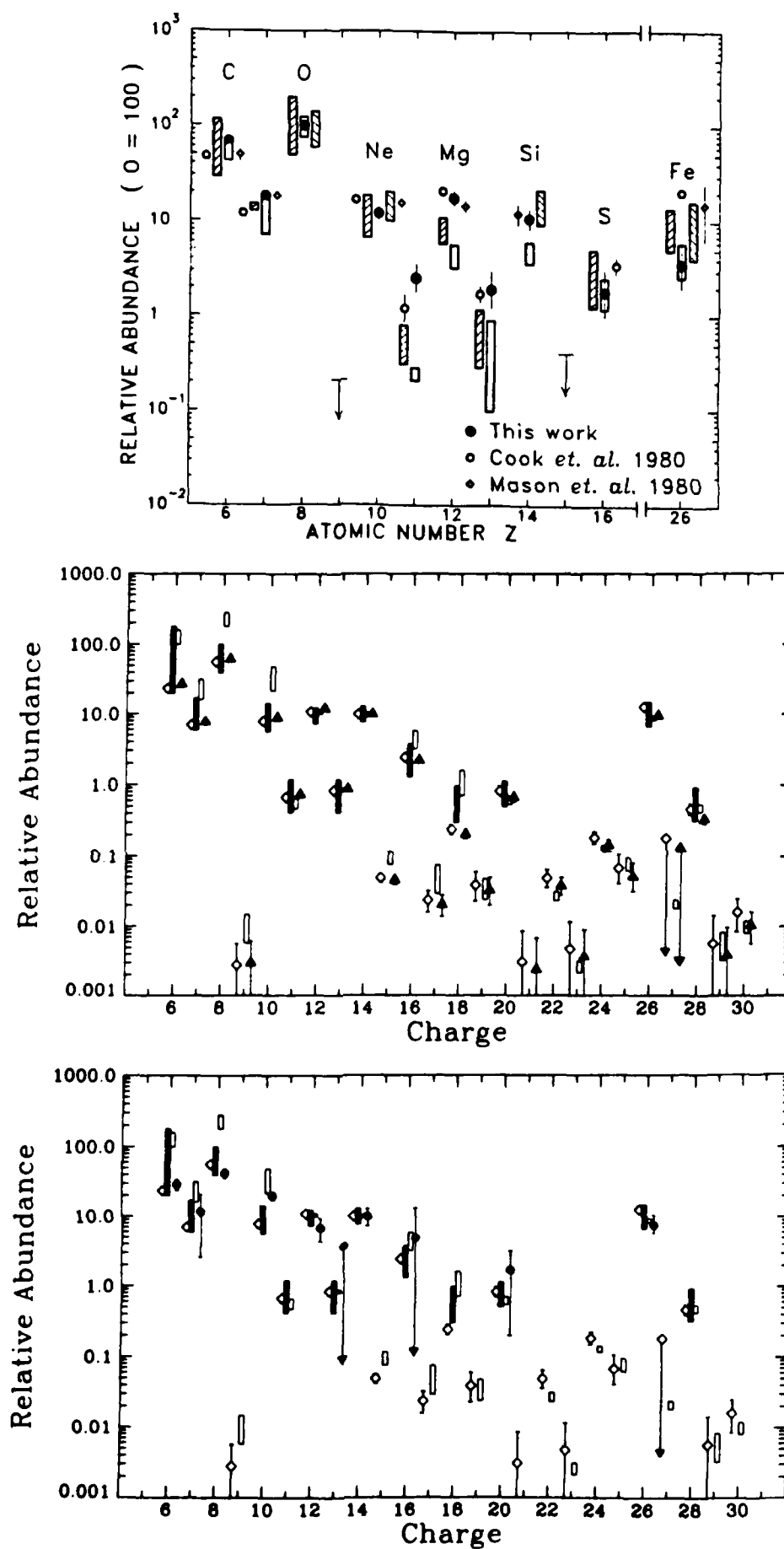


FIGURE 1: Comparison of SEP Element Abundances

The goal of this work is to assess the degree to which current measurements and interpretations are consistent and present a coherent picture of the solar flare/particle acceleration process and to point to the needed directions for future experimental and analytical work in this field.

An example of this effort is shown in Figure 1 where the top plot compares the ONR-602 observations of the elemental composition of the solar energetic particles observed during 1982 to observations by other groups on different sets of flares and to abundances measured on the sun. The overall agreement is quite remarkable, although some interesting effects, e.g. the element magnesium, remain to be explained. In the middle plot, a compiled set of average solar energetic particle abundances and the expected coronal abundances derived from them (diamonds and filled triangles -- from Breneman and Stone, 1985) are compared to measured coronal (filled boxes) and photospheric (open boxes) abundances. The agreement of the particle data with the abundances in the solar corona is quite good while the correlation with photospheric abundances is not as good. The conclusion here is that the solar energetic particles have their origin in the solar corona rather than in the denser photosphere.

The gamma ray line observations of solar flares (Murphy et al., 1985) provide another source of information on the solar flare process. These gamma ray lines are produced by the accelerated particles interacting with the ambient medium producing excited nuclei which decay by gamma ray emission. Analysis of the 0.5 MeV line has indicated matter densities such as are found in the solar chromosphere. The bottom plot on Figure 1 is the same as the central plot (without the derived coronal data points) except that chromospheric abundances derived from gamma ray line observations have been added as filled circles. While the uncertainty on this new technique is still large, the overall trend of the data shows agreement with the solar energetic particle data and the coronal abundances. The best agreement is for O, Mg and Si, while Ne shows a clear discrepancy. Thus, the current results are indicative, but additional work is required before the full picture is known. However, the use of gamma ray line derived abundances is an important new technique which will complement the observations of solar energetic particles, and correlated observations of both (on the same flares) are called for in order to resolve many of the outstanding questions.

B. Data Reduction, Programming and Instrument Response

In our previous work with the Phoenix-1 dataset, we uncovered a number of problems with the data on the CHART (second generation, compressed counting rate) tapes which lead to ambiguous interpretations of the data. In particular, the CHART tapes have been zero-compressed which leads to ambiguities in the rates during periods of less than 100% data coverage. In addition, header records appear only 1/16th as often as on the PHRET tapes, requiring a large amount of interpolation of the geophysical parameters. These problems have limited the work we can do on, for example, the South Atlantic Anomaly (SAA) region. The discrepancies can be resolved, however, by looking at the PHRET (uncompressed, time-ordered, raw data) tapes, and we have obtained a copy of these tapes from the University of Chicago. The PHRET tapes are written at 6250 BPI and can only be read on the EPDS. This has necessitated developing software routines to read, decode and rewrite the sequences in DEC format. These routines have been written, tested and debugged during the past year and are now in use for the analysis of the SAA passes.

Previous work on the instrument response has focussed on the energy ranges and particle species recorded by both the monitor telescope and the main telescope counting rates. An additional part of the instrument response is the assessment of the background contribution to the counting rates. This is particularly important for the monitor telescope where the preliminary analysis has shown unexpectedly high MM and MH counting rates (corresponding to low energy alpha particles and $Z \geq 3$ nuclei) at low altitude over the SAA. The possibility exists that some of these counts may be due to large angle protons penetrating the passive shielding around the monitor telescope.

To investigate, quantitatively, this latter possibility, we have been working with a Monte Carlo program into which we build both the passive shielding and the active detector volumes. Protons (or other particles) are then selected for random incidence on the instrument and followed through the passive shielding into the detector volume, and their signal in the detector is calculated. In this way we can isolate any trajectories through the system which result in signals of a specific level (and determine their solid angle) and can study the efficiency, as a function of energy, for incident particles to produce counts in the instrument. Such studies are the only way to assess this particular type of background and are necessary to insure confidence in the experimental results. The program modifications have been completed, the monitor telescope is being built into the program and detailed calculations will be done (as computer time is available) over the next few months.

C. Magnetospheric Particles: Low Energy Equatorial Protons

1. Spatial Distribution:

During the past year we have focussed attention in our magnetospheric investigations on the low energy protons observed near the equator. Figure 2 shows raw data for individual passes over the geomagnetic equator taken from different geomagnetic longitudes (ϕ). There is some intensity variation from one pass to the next, but the more striking result is that the peak occurs at different geomagnetic latitudes depending upon the geomagnetic longitude in this dipole representation. Previous investigators (Hovestadt et al., 1972; Moritz, 1972; Mizera and Blake, 1973) on the Azur and OV1-17 satellites at significantly higher altitude observed particle peaks at the equator or at the minimum of B/B_0 .

The many equatorial passes made by the S81-1 mission gives us an opportunity to investigate the location of the maxima in particle flux at altitudes well below those of previous missions to look for spatial diffusion effects. Binning the data in 10° longitude bins, as illustrated on the top part of Figure 3, produces sharp peaks whose center can be well located in geomagnetic latitude. The FWHM of these peaks is $8-10^\circ$. Using 5° longitude bins, we have been able to trace the location of the flux maxima, and the results are shown on the lower portion of Figure 3. The deviations from the magnetic dipole equator follow, within the uncertainties, the minimum B equator in agreement with the higher altitude results. The width of the peaks is somewhat narrower than observed previously giving no indication of diffusive broadening. Thus, the interpretation of these results are that the particles are "trapped" near the altitude of observation rather than diffusing inward from a higher altitude region. This implies that the process of charge exchange neutralization followed by restripping/trapping continues down to the

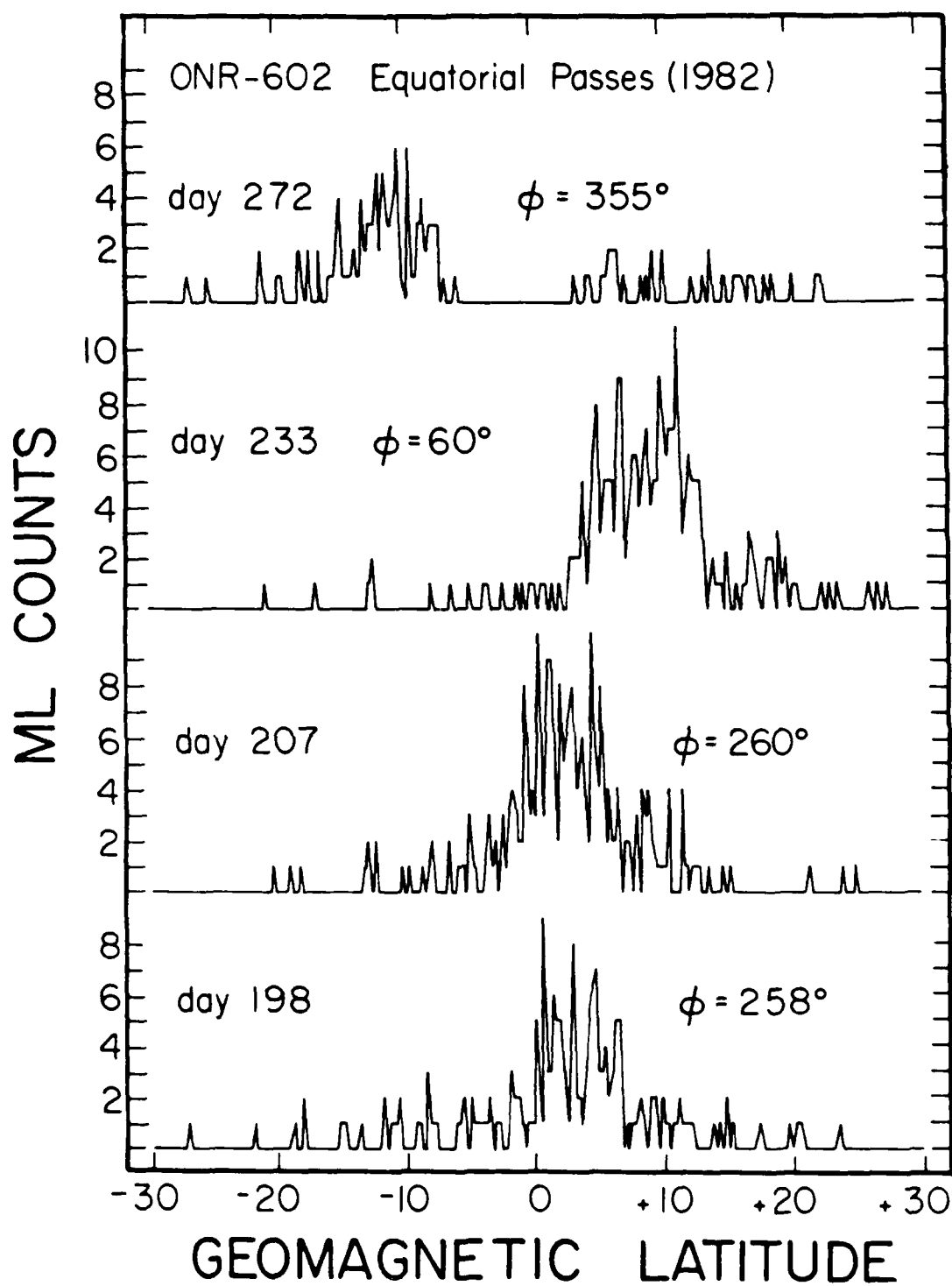


Figure 2: Individual Equatorial passes observed by ONR-602.

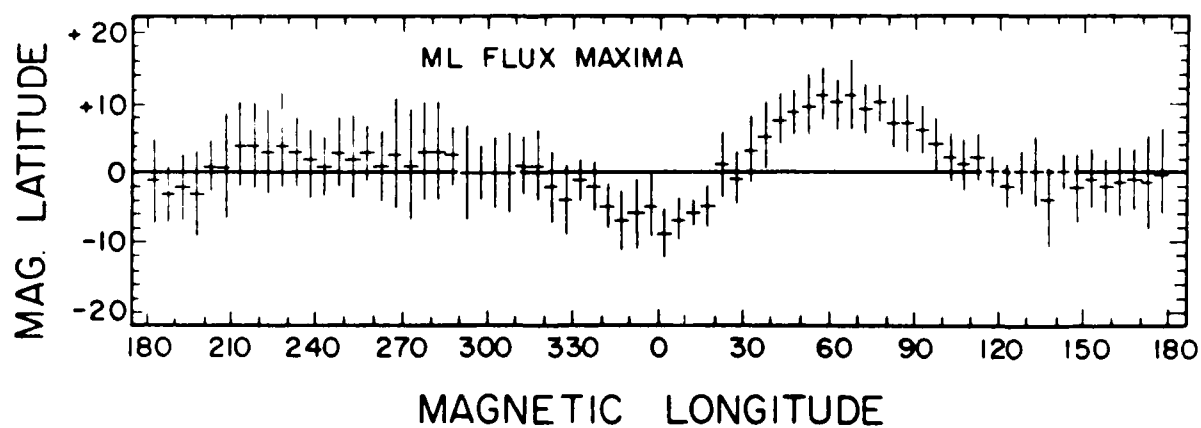
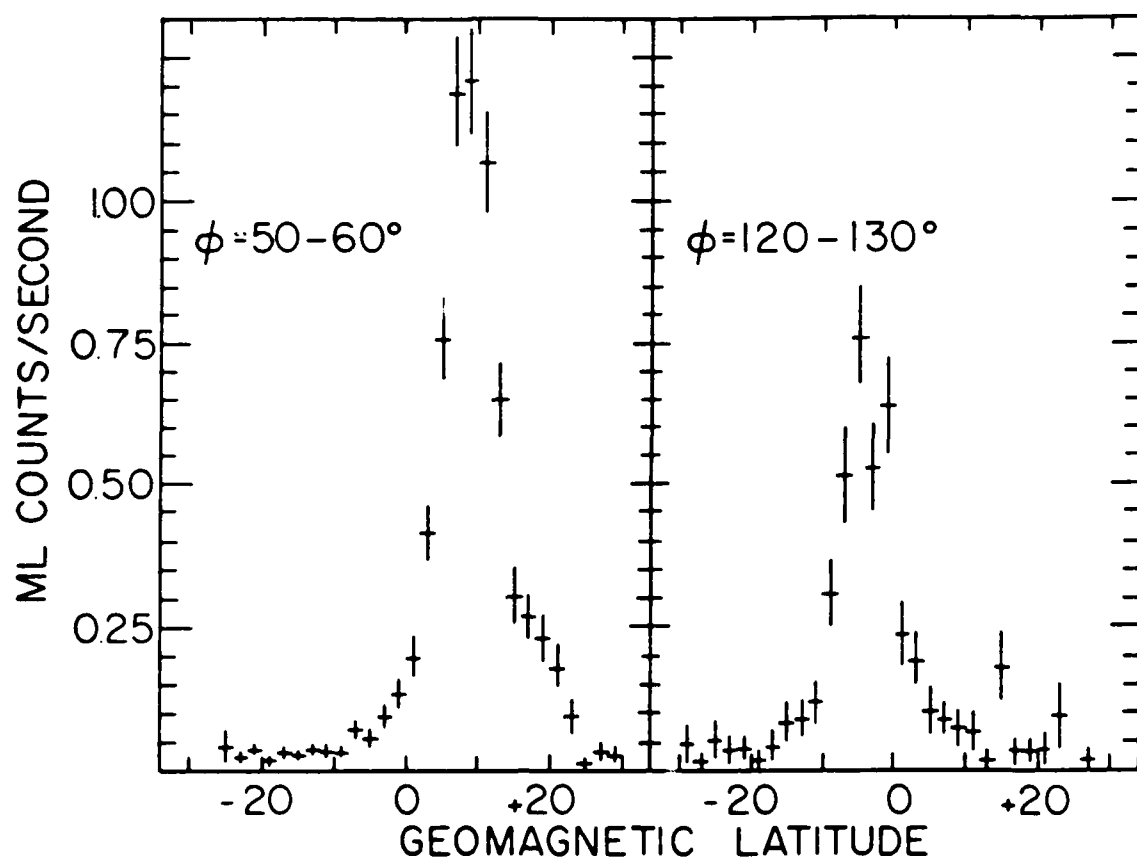


Figure 3: Latitudinal profile (top) and location of maximum (bottom) for protons at low altitudes.

altitudes sampled by the S81-1 mission (180-280 km).

"Prolss (1973) attempted to use the charge exchange mechanism to calculate the location of the maximum energy deposit in the atmosphere at altitudes of 130-160 km for comparison to airglow observations. He found that for protons of very low energy (10-40 keV), the maximum energy deposition occurs 10-20° off the magnetic dipole equator, which for the actual geomagnetic field corresponds to the minimum B equator. Maximum energy deposition does not necessarily imply maximum particle flux since non-vertical trajectories are important, but the present observations limit such calculations by requiring that the maximum particle flux be confined to the equator down to ~ 250 km altitude. In this regard, the EUV observations of emission from excited He⁺ and He (Meier and Weller, 1975) are relevant. The observed spatial distribution of the EUV maxima, where they can be compared, agree well with the lower plot on Figure 3. This argues that the ions producing the emission are themselves precipitating, probably from the ring current.

2. Altitude Dependence:

The orbit of the S81-1 mission varied in altitude over the duration of the mission from ~180 km to ~280 km. Previous observations reported no apparent altitude variation in the proton intensity from ~400 km to 1000 km. Over the limited altitude range sampled by the S81-1 mission we have been able to investigate the altitude dependence by binning the dataset into altitude ranges using the satellite altitude at the flux peak as the parameter. All passes falling within a given altitude range were superposed to obtain a mean peak flux, and comparison between different ranges showed a surprisingly large variation. Figure 4 shows the Phoenix-1 data compared to the altitude dependence of other measurements found in the literature.

A least squares fit to the Phoenix-1 results shows a power law dependence on altitude, H^{β} , with exponent $\beta = 5 \pm 0.5$. This dependence is essentially the same as that reported for 55 MeV protons observed over the SAA by Filz and Holeman (1965) but is slightly steeper than the newer 55 MeV proton data reported by Parsignault et al. (1981). For very low energies, Goldberg (1974) reports an even steeper altitude dependence. The 55 MeV proton results show the altitude dependence continuing without noticeable change in slope up to ~700 km, well into the region reported by Mortiz (1972) to show no altitude dependence for protons around 1 MeV.

The altitude dependence is explained as increasing particle loss with decreasing altitude due to interactions with the increasingly denser atmosphere. This mechanism can explain, qualitatively, the results up to ~400 km but would predict a flattening at higher altitudes. We are currently working on a quantitative calculation to reproduce the altitude dependence in the Phoenix-1 range which can then be used to investigate the apparent inconsistencies at higher altitudes.

The altitude dependence is extremely important for comparing the absolute flux of precipitating protons measured in 1982 by Phoenix-1 with the previous observations about a decade earlier in order to search for temporal variations in this particle population. The previous observations in a comparable energy range were made at ~ 450 km altitude, and we have assumed, following the results on Figure 4, that the derived power-law altitude dependence holds at

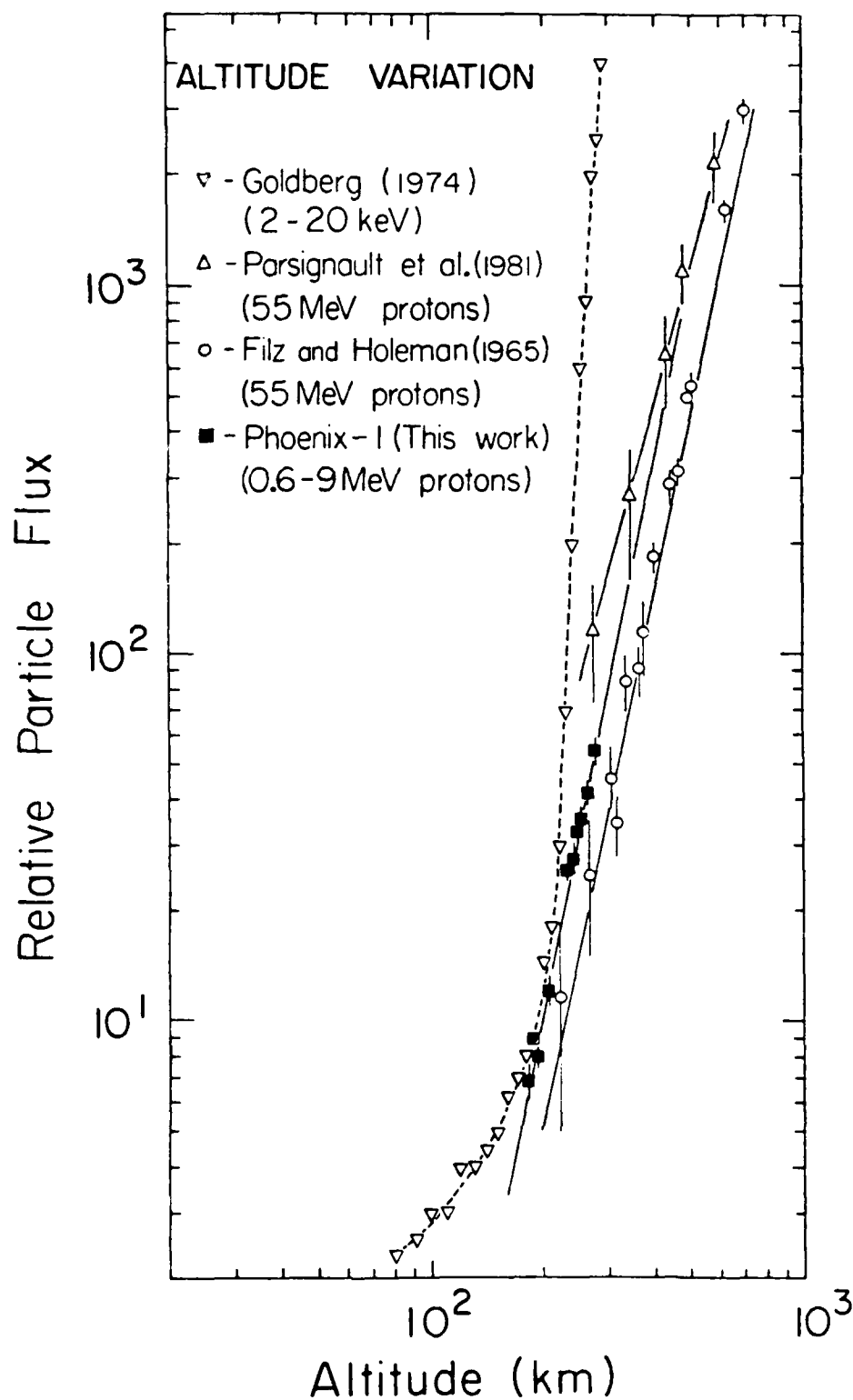


Figure 4: Altitude dependence of proton flux.

least up to 450 km.

2. Energy Spectra:

In order to investigate the energy spectrum of the equatorial protons we have compiled previous observations ranging in energy from 10 keV to several MeV. The results are shown on Figure 5. At the lowest energies the fluxes show large variability with geomagnetic conditions, and results are presented for both pre-storm and post-storm conditions. At energies above several hundred keV the dependence on geomagnetic conditions lessens, and single day, pre-storm values are equivalent to long period averages, as long as large storms are excluded from the averages. Post-storm conditions show enhanced fluxes up to MeV energies. The Phoenix-1 mission data corresponds for these definitions to average data since no periods following large storms are included in the dataset. Therefore, we have fit a power law in energy to the previous data above several hundred keV for pre-storm or average conditions, and the result is shown as the solid line characterized by an energy dependence $E^{-\gamma}$ with exponent $\gamma = 2.55 \pm 0.11$. Such a power law may not be the best representation for the energy spectrum. A curve which falls off more steeply at high energy would also give a reasonable fit to the high energy data, but the existing measurements are not sufficient to choose between these possibilities.

The proton energy range covered by the Phoenix-1 ML counting rate is 0.6 - 9.1 MeV. For the power law spectrum, the mean energy is ~1.3 MeV. For a steeper spectrum at high energy, the mean energy is reduced. The differential flux measured by the Phoenix-1 instrument is plotted as squares on Figure 5 with the full energy interval indicated. The open square represents the measured intensity corresponding to an altitude of ~ 270 km. Using our measured altitude dependence, this result was extrapolated to an altitude of ~ 450 km and is shown as the solid square. Integration of the power law spectrum discussed above over the Phoenix-1 energy range produces only about a third of the extrapolated Phoenix-1 flux.

The highest energy point of Moritz (1972) falls well below the best fit power law line and might indicate a cut-off in the energy spectrum. Assuming no particles above 2 MeV, the Phoenix-1 point would be increased to a value of 3.6×10^{-2} protons/cm²-sr-s-keV, well above the values reported by Hovestadt et al. (1972) and Moritz (1972) in similar energy ranges. Turning the problem around, the power law energy spectrum needed to fit the extrapolated ONR-602 observations is shown as the dashed line on Figure 5 and is clearly in disagreement with the previous data. Thus, we conclude that the flux of precipitating protons at the equator is larger in 1982, by roughly a factor of 3, than it was during the 1969-1971 time period of the previous observations.

The origin of this flux increase is currently under investigation. The "standard" explanation for these low energy particles at the equator involves charge exchange of ions in the ring current. If the ring current intensity increased by a factor of three, that would explain the results, but there is no evidence for such an increase. Alternatively, the charge exchange rate may have increased due to differences in atmospheric density, solar/geomagnetic conditions, etc. and we are analyzing such effects. If none of these appears able to account for the flux increase, this would call into question the "standard" charge exchange model or require an additional process to be

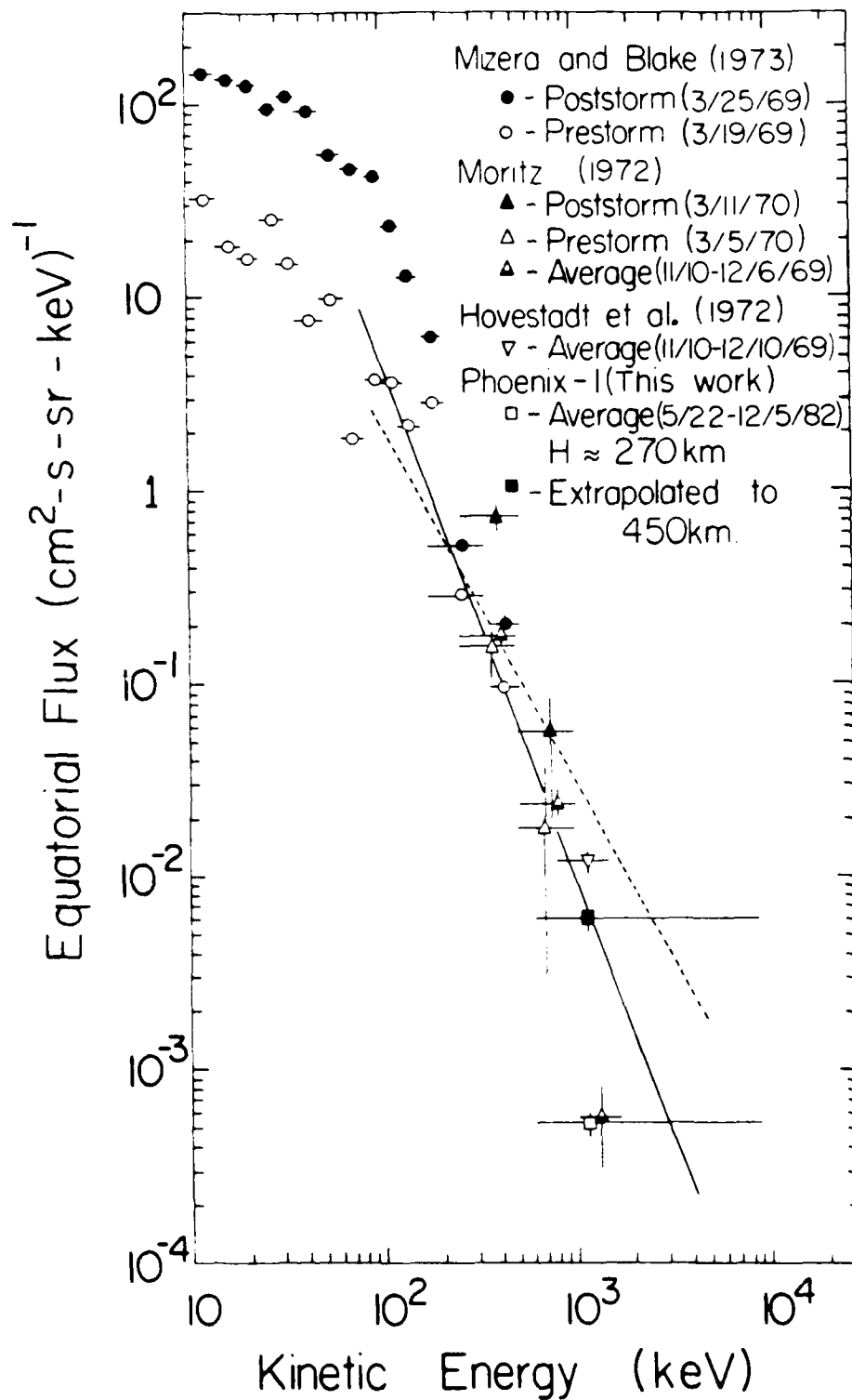


Figure 5: Differential Energy Spectrum for equatorial protons.

active. Further analysis is needed to decide between these interesting possibilities.

D. ONR-604 on CRRES

Our effort during the past year on this aspect of the project has involved support of the CRRES/SPACERAD Science Team, convened by AFGL to plan for the scientific and engineering analyses to be conducted with the CRRES dataset, working on data processing/analysis plans for the ONR-604 dataset, and planning for the interpretation of the data in terms of the interplanetary heavy ion environment for both quiet (galactic particles) and disturbed (solar energetic particles) periods.

The heavy ion radiation environment encountered in near-Earth space consists of three major components: (a) galactic cosmic rays (GCR), (b) solar energetic particles (SEP), and (c) trapped magnetospheric particles. The first two of these arrive at the earth from outside our immediate geospace environment and are termed "interplanetary" while the last resides within the Earth's magnetosphere, and is termed a "local" component. The interplanetary particles encompass a wide range in both energy ($E > 500$ keV) and charge ($1 \leq Z \leq 96$). Some of these particles penetrate the Earth's magnetic field and form part of the radiation environment in which spacecraft must operate.

An important objective of the CRRES program is to investigate the effects of the space radiation environment on the modern microelectronic components that will be used in future spacecraft. One of these effects is the ability of single intensely-ionizing particles to upset the logical state of a single bit in a digital microcircuit, causing a single event upset (SEU). The MicroElectronics Package (MEP) onboard the CRRES satellite will measure SEU rates in a large sample of digital components. In addition, other engineering experiments on the CRRES spacecraft will investigate radiation effects to other types of spacecraft structures. The fundamental input required for any assessment of radiation effects is the type, intensity, directionality and energy spectrum of the incident radiation. This may in terms of the energy spectra of individual particle species or, in some cases, in terms of the overall Linear Energy Transfer (LET) spectrum of the radiation.

The data from the CRRES particle sensors will provide simultaneous measurements to characterize the environment being sampled by the engineering experiments. However, detailed characterization will require significant amounts of data analysis effort and, consequently, extended periods of time. For heavy ions, likely to be the most important component producing effects in the MEP, the principal source of data on CRRES is the ONR-604 experiment. At lower energies, the AFGL-701 boxes can provide some complementary heavy ion data, and the AFGL-701 experiment will trace the proton spectrum better than can be done with ONR-604. Thus, it will be necessary to combine data from a number of sensors to determine the particle environment surrounding CRRES.

During the past year this problem has been addressed by a sub-group of CRRES investigators consisting of J. Wefel, Louisiana State University, D. Chenette, Aerospace Corporation and J. Adams, Naval Research Lab. This sub-group has devised an approach involving combining the CRRES data from selected sensors, analyzed in three month subsections, with an Interplanetary Heavy Ion Model developed at NRL to provide timely inputs to the analysis programs for

the engineering experiments. The data flow for this approach is shown in Figure 6, involving five laboratories.

AFGL is responsible for raw data processing to provide Agency tapes to experimenters. In addition, they will maintain a Geophysical Data Base of CRRES data and will supervise Product Associated Working Groups who will be utilizing CRRES data. (One of these will be the MEP analysis group.) Agency tapes are supplied by AFGL to the University of Chicago and the Aerospace Corporation who perform the necessary first phase raw data processing. For ONR-604, the result of this processing is the PHRET tape (similar in format to the Phoenix-1 PHRET tapes with which we are now working), a copy of which is sent to LSU. The LSU and the Aerospace groups will then extract from the relevant instruments the fluxes of protons, alphas, and selected abundant high-Z nuclei such as C, N, O, Si, Ca, Fe group, in energy the intervals defined naturally by the instrument operating modes. This data is sent to NRL where it is compared to the Interplanetary Heavy Ion Model. The parameters of the model are then adjusted to give the best agreement with the CRRES data, and these parameters are transmitted to the Product Associated Working Groups (who already have a copy of the computer model) and used by them to calculate the particle fluxes needed in their analysis.

In this way, the working groups obtained the particle environment, corrected to the actual CRRES particle data, without having to fully analyze all of the particle sensor data, a task that is impossible on short time-scales. Periodically, say every year, the overall dataset will be used to tune the model parameters for the average conditions corresponding to the full time period.

Current efforts are directed towards using the ONR-604 calibration data to define the energy and charge ranges most useful for this analysis and in delineating the tasks and software developments needed to permit the proposal of Figure 6 to be used for the CRRES program.

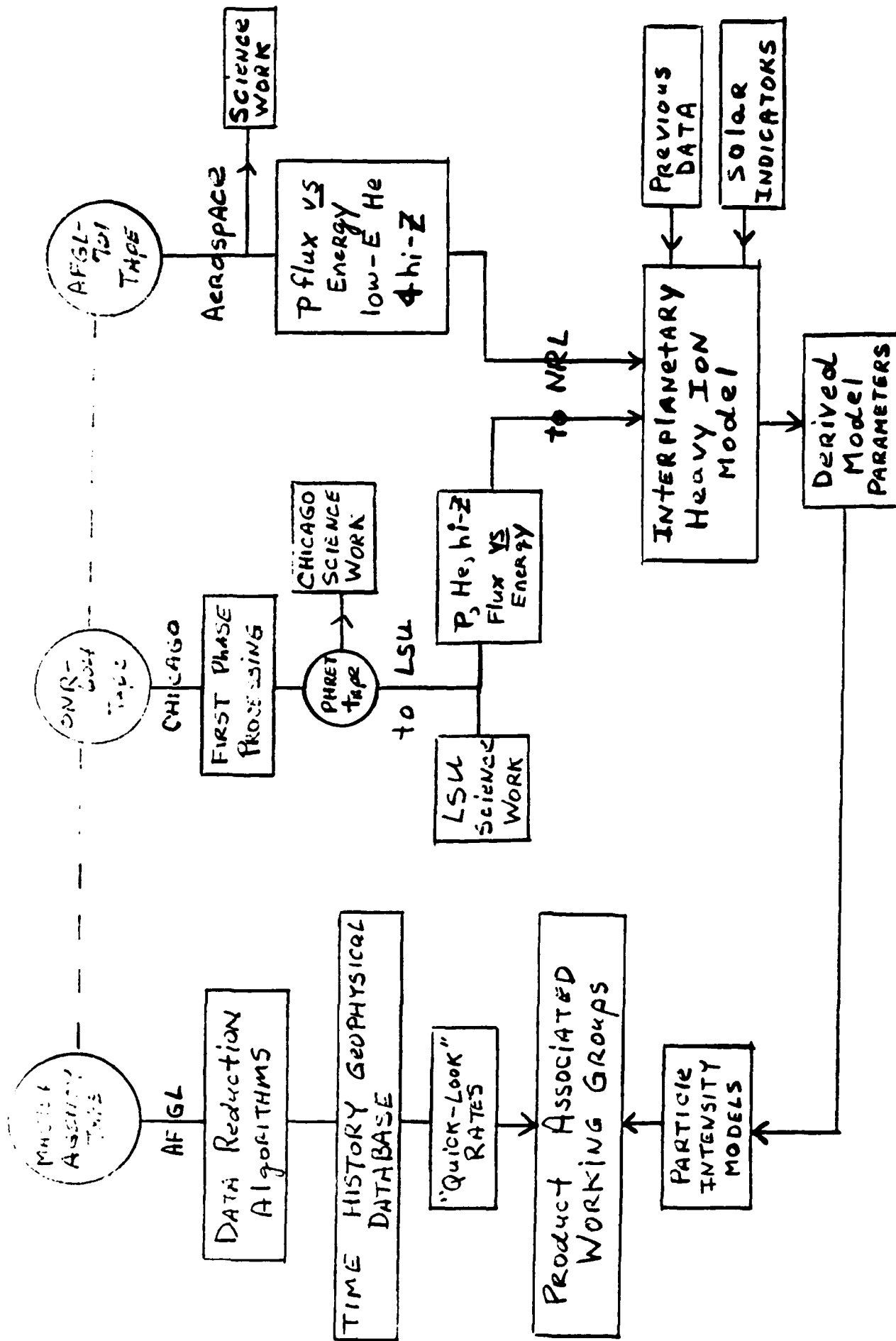


Figure 6. Data flow for the analysis of the Interplanetary Heavy Ion Environment during the CRRES Mission.

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